Fractional Crystallization and the Palisades Sill
William Bruner
570 thesis

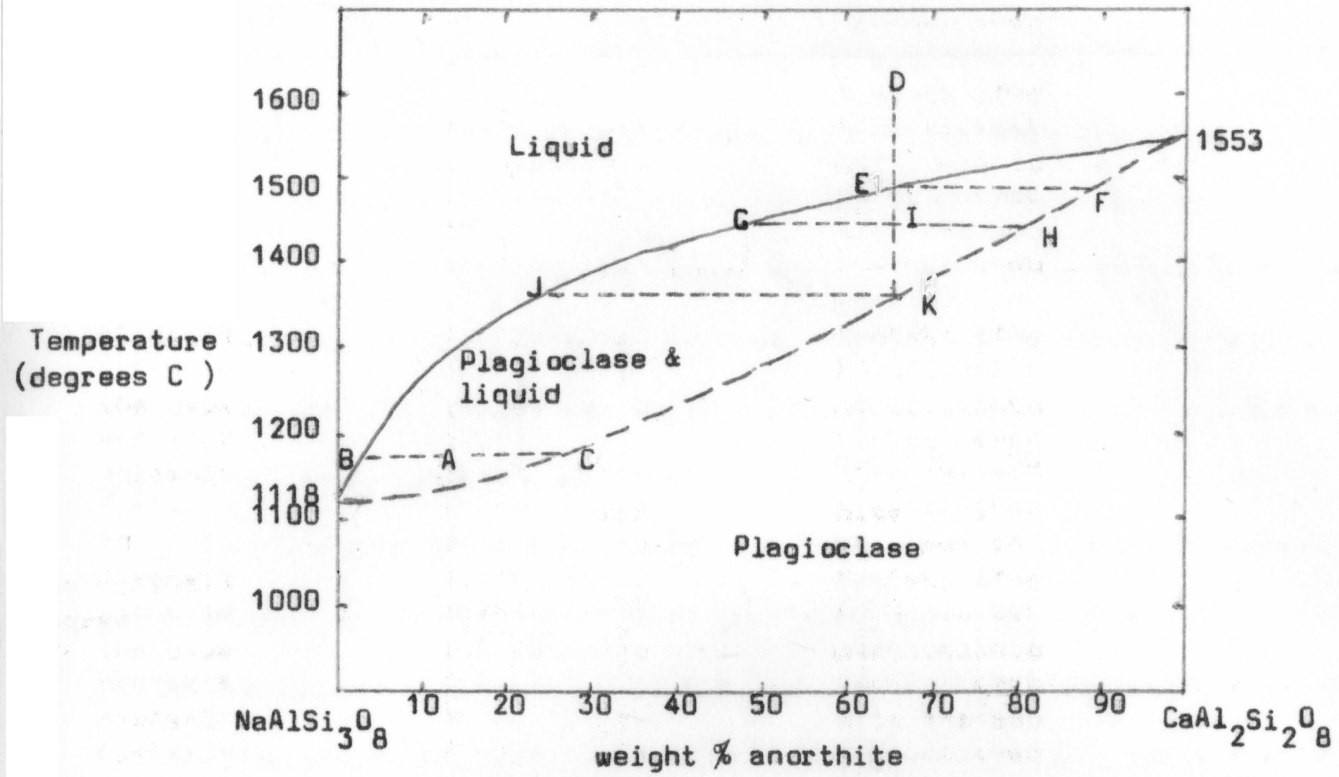
Advisor: E. G. Ehlers
June 8, 1983

This paper discusses the various processes by which different igneous rocks are formed from the same parent magma. The discussion covers also the Palisades Sill, the best known example of gravity fractionation.

Magmatic differentiation covers all processes by which a magma, initially homogenous on a large scale, ultimately gives rise to igneous rock masses of contrasted composition. Of all the possible processes which could conceivably change the composition of a cooling magma, differentiation by crystallization is one of the most easily understood. As the principle rock-forming minerals are generally solid solutions, the initially precipitated compositions of each mineral are, in general, enriched in the high-temperature components in relation to the liquid from which they have precipitated. The minerals which are mutually associated during crystallization are those which precipitate over the same temperature range. There is an equally strong tendency for antipathy between minerals of widely different temperature ranges. As soon as crystallization starts, particularly in zones of low pressure, the composition of the residual liquid differs both from the initial liquid and the first batch of crystals; in short, the liquid is differentiated.(Carmichael, Turner, Verhoogen 1974)

Further understanding of differentiation processes may be gained by examining the solid solution series of the plagioclase feldspars, which form one branch of Bowen's Reaction Series. The system was first examined by Bowen in 1913, and was one of the first to be investigated for geological and ceramic interpretation.

Phase diagrams of this and any solid solution are characterized by two curves. Above the upper curve(the liquidus) is a field consisting of a liquid phase; below the lower curve(the solidus) is a field consisting of a solid phase. Between the liquidus and solidus curves, liquids and solids coexist. The compositions and relative amounts of coexisting liquid and solid phases are found by means of a horizontal tie line. A sample of the composition and temperature of



A consists of liquid of composition B and crystals of composition C. We know from the Lever Rule that the length of AC is proportional to the amount of liquid present and the length of BA is proportional to the amount of crystals present.

The Arrangement of liquidus and solidus lines in systems of this type leads to an interesting type of crystallization. A liquid D, when cooled to the liquidus at E, begins to crystallize; the first-formed crystals are of the composition F. As the crystals are richer in the anorthite component than the original liquid, this causes the composition of the remaining liquid to become enriched in the albite component. A consequence of this change in liquid composition is a depression of the freezing point of the liquid, which follows the path shown by the liquidus line. But as can be seen by examining the horizontal tie lines, the liquid of changed composition cannot exist in equilibrium with crystals that have been previously precipitated; that is, a liquid of composition G can coexist stably only with crystals of composition H, rather than with the crystals of F which were formed earlier. The liquidus line shows how the liquid changes in in composition as it cools; at each point on the liquidus, the liquid precipitates only crystals that are in equilibrium. Simultaneously, the liquid reacts

with previously formed crystals by diffusion and changes their composition. Thus, as the liquid continuously changes in composition from E to J along the liquidus, the composition of all previously precipitated and precipitating crystals simultaneously and continually changes from F to K . By the time the crystals are of composition K, they have the same composition as the original liquid D, and the last of the liquid is consumed. The plagioclase remains stable with cooling to room temperature.

In systems of this type, where continuous reaction takes place between a changing melt and previously formed crystals, there is always a possibility of incomplete reaction due to nonequilibrium conditions. Incomplete reactions are common in both natural and synthetic plagioclase-containing systems as a result of variation in the rate of crystallization. The end-products of incomplete reaction between such a cooling melt and earlier-formed, calcium-rich crystals are compositionally zoned plagioclases with rims more sodic than the core. Such compositional zoning may be sharply defined or gradational, depending on the cooling history. If the cores of the plagioclase crystals are more calcic than the bulk composition of the system, it follows that the outer rims are more sodic than the bulk composition. This requires that the final melt composition changes further in the direction of the sodic component than would be expected under equilibrium conditions.(Ehlers, 1972)

Fractional crystallization depends on nonreaction or incomplete reaction of the magma with its crystalline products. A number of mechanisms have been suggested to prevent reaction, the most significant of which appears to be gravitative differentiation.(Ehlers & Blatt, 1982)

Fractional crystallization is any process by which early formed crystals are prevented from equilibrating with the liquid from which they grew. Thus, a basaltic magma could give rise to a succession of residual liquids, each of progressively changing composition; and for each liquid fraction there would be

a complementary crystal fraction, represented either as an accumulation of crystals or as zones of changing composition within each mineral. Each fraction, liquid or solid, could become a separate rock of unique composition. The broad chemical pattern of fractional crystallization is for successive residual liquids to become enriched in silica and the alkilis, and in iron relative to magnesium. Since most minerals form solid solutions, they tend to be enriched in their respective high-temperature components, namely magnesium, calcium, and aluminum compared to later crystal or liquid fractions.

Gravity fractionation is generally considered to be the sinking of crystals of heavy minerals in a less dense liquid, although floating of low density crystals has been suggested as well. It is most effective in the early stages of evolution when the liquid phase is still dominant and has not yet become too viscous or too dense to prevent settling of the crystals. The crystals of earliest formation in most basaltic rocks belong to comparatively dense minerals like olivine, pyroxene, or a lime-rich plagioclase. Basal layers rich in olivine, pyroxenes, and iron ore in the large basic intrusions illustrate the effectiveness of crystal settling from slowly moving bottom currents of liquid. Floating of light crystals has been far less commonly observed, and leucite is the prime example. Sahama(1960) has observed giant leucite crystals floating on the surface of a lava lake, and the concentration of small leucite crystals along the roof of the Shonkin Sag dike of Montana could have originated in the same way.

Model experiments on a fluid flowing with suspended particles show that the partickes migrate toward the higher-velocity(axial) region, indicating that a flowing magma could redistribute and concentrate suspended crystals by flowage differentiation. Provided that the flow is laminar, a state that depends on velocity, viscosity, and the shape and size of the conduit, the suspended crystals migrate to the axial zone of the flowing magma. It is probable that the axial concentration of the crystals persist as the magma is intruded as sill, and

later modified by gravity differentiation.(Carmichael, Turner, Verhoogen 1974)

The separation of crystals from the melt also can be accomplished by squeezing the liquid away from the solids; this is analogous to the squeezing of a sponge. Bowen likened the process to a filter press. Pressure, therefore, comes into play as an effective means of crystal separation. This process is termed crystal filtration. The weight of the crystal mush at the bottom of the chamber tends to squeeze out the liquid.

Magmatic differentiation can come about as a result of non-fractination processes. One of these is the process of gaseous transfer.

The volatile constituents in a magma are capable of dissolving solids and liquids within the magma. If a gas phase escapes from the magma, the dissolved material is transferred to the country rock as impregnations or vein fillings. The mechanism of gaseous transfer involves the equilibrium between gases, solids, or liquids, depending upon the the temperature and pressure conditions. In a large body of magma the difference of pressure between the upper and lower levels is very great. Reaction between the constituents dissolved in the gas phase and the surrounding magma continuously occurs as the gas phase rises. There involves mutual exchange of matter; consequently, the composition of the gas as it reaches the roof is different from that which it possessed at depth. Gaseous phases are therefore capable of modifying the composition of enclosing magma as it rises.

Another nonfractionation process that can affect the composition of the rocks formed from an igneous melt is through the assimilation of country rock that is surrounding the intrusion. Magmatic stoping is the incorporation of xenoliths which are fragments of the walls that envelope the intrusion. The broken rock results from the stress imposed on the country rock by the intruding body during doming. Conditions favorable for stoping must include specific gravity ratios sufficient to allow the roof fragments to sink and react with

the surrounding magma.

In areas where erosion has been great, so that deep conditions can be observed, it can be seen that the doming of the country rock is not feasible. Consequently, there is less fracturing of the roof by stress and less xenolithic incorporation. Instead of this fracturing of the roof, magmas penetrate the walls and roof and saturate them with magmatic fluids. This soaking is especially evident where the country rock is foliated. Sediments are particurlarly susceptible to magmatic saturation and produce lit-par-lit injected gneisses. Reactions between such sediments and magmatic fluids are readily seen in the gneisses found in the core of mountains.

In magmatic saturation, solutions percolate through the country rock, adding some substances and subtracting others. Where the country rock is schist, the injection is in the form of lit-par-lit saturation; where it is massive, such as quartzite, soaking is uniformly distributed. The composition of some of these soaking solutions would seem to be of the nature of hydrothermal solutions, while others, presumably later, appear to consist of magmatic liquids. As the process continues, the country rock is made over into an igneous rock(having all the properties of a normal member of that group).(Alling, 1936)

Magmatic mixing is occasionally a factor in the differentiation of igneous rocks. Cited in support of mixing is petrographically obvious evidence of disequilibrium; for example, widespread association of plagioclase phenocrysts of markedly different composition in andesites and dacites. Other explanations are possible and are given precedence in some recent investigations. Failure to establish equilibrium is likely during assimilative reaction between basic magma and a granitic wall, or when crystals sink down a vertical composition gradient in a differentiating magma body.(Carmichael, Turner, Verhoogen, 1974)

Of all the processes mentioned, gravity fractionation is the most significant causes of magmatic differentiation. One of the most well-known examples of

gravity fractionation is the Palisades Sill of the Hudson.

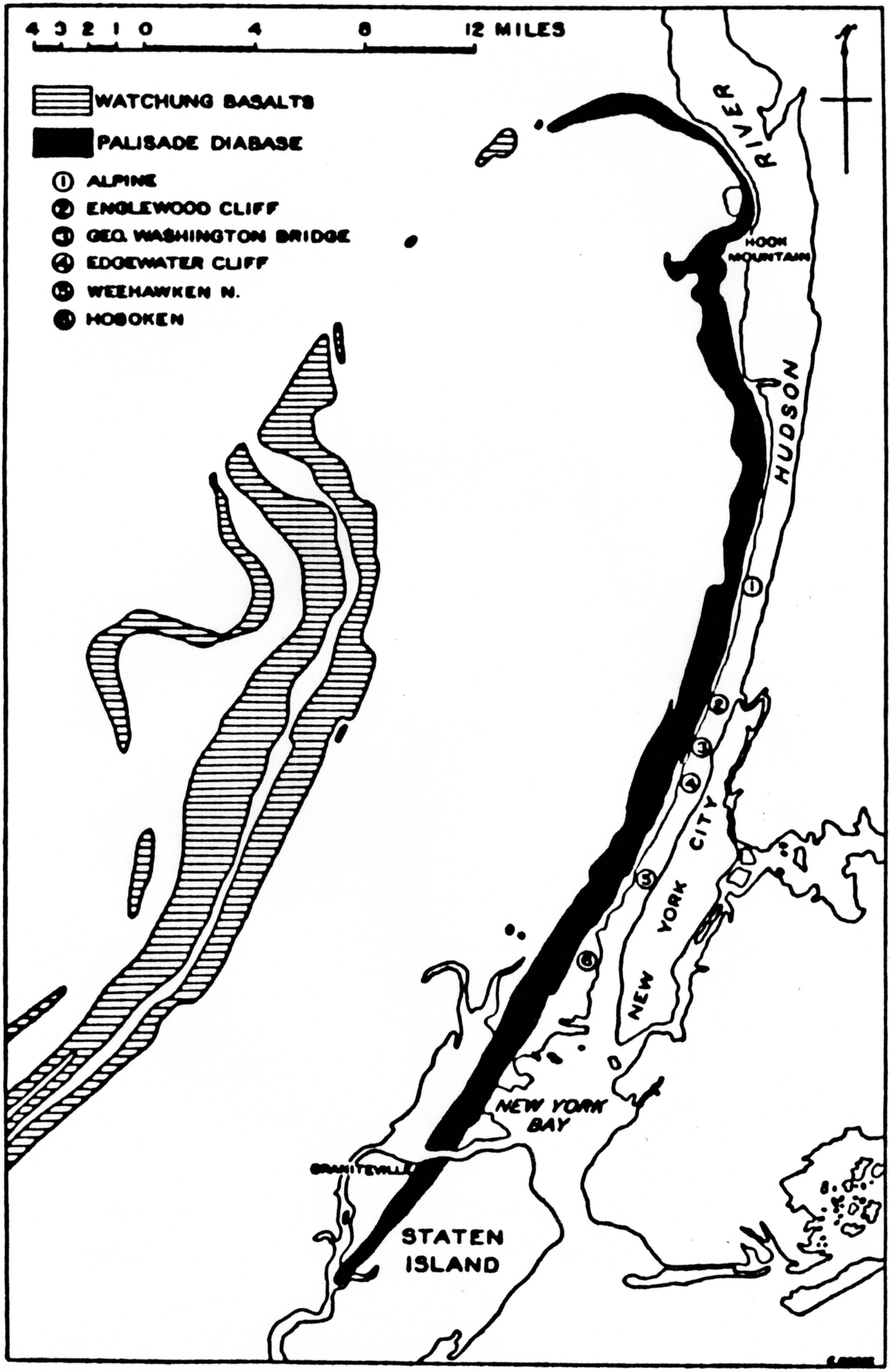
THE PALISADES SILL

Location: Late Triassic diabase bodies, including the 1,000-ft. thick Palisade Sill outcropping along the west bank of the Hudson River adjacent to New York City, extend in a narrow belt for more than 250 miles from southeastern New York state to northern Maryland. Basaltic magmas invaded postorogenic terrestrial arkoses and shales of Triassic age and are related to surface flows farther west. These dark-colored rocks, predominantly sills, are characteristically columnar-jointed, forming steep escarpments and cliffs.(Hyndman, 1972)

The Palisades Sill crops out in New Jersey and New York states and forms in part the Palisades along the Hudson River, west and north of the city of New York. Its outcrop extends from Staten Island in the south, to Haverstraw in the north, then from there west to Mount Ivy, a distance of about fifty miles. It is up to one and a half miles wide. The outcrop at Jersey City rises above the low-lying country there and to the south. From Weehawken north to Haverstraw it forms the western bank of the Hudson River, except in the Nyack area, where it curves inland at Piermont and back to the river bank at Verdrietege Hook. From here it reaches its highest point, 827 feet, at High Tor, and then swings back inland to Mount Ivy with loss of relief, and again passes beneath the surrounding sediments north of Pomona.(K. Walker, 1969)

General Geology: The Palisades Sill is intruded into Triassic arkoses and shales of the Newark formation, which has a westward dip of about fifteen degrees. West of the cliff line, ice erosion has scratched and polished many surfaces. The sill disappears below the Newark formation which fringes the marshy alluvial flat of the Hackensack River.

The lower contact of the sill is better exposed than the upper. It is seen at intervals all the way from Hoboken to Alpine, but the best and most continuous sections are observed along the Hendrik Hudson Drive both north and south of the


4 3 2 1 0 4 8 12 MILES
WATCHUNG BASALTS
PALISADE DIABASE
① ALPINE
② ENGLEWOOD CLIFF
③ GEO. WASHINGTON BRIDGE
④ EDGEWATER CLIFF
⑤ WEEHAWKEN N.
⑥ HOBOKEN
HUDSON RIVER
HOOK MOUNTAIN
NEW YORK CITY
NEW YORK BAY
GRANTVILLE
STATEN ISLAND

George Washington Bridge. Transgressive contacts are visible at King's Point, Weehawken, though the sill on the whole is concordant. Slabs of arkoses and shale have been floated up by the diabase in many places, and at Weehawken cliff a large slab of arkose stands vertically in the more slowly cooled portion of the sill far above the lower contact.

From Jersey City to Alpine near the base of the sill is an olivine layer or ledge averaging fifteen feet thick. This layer is darker and usually weathers more readily than the normal diabase and is therefore conspicuous on cliff faces, particularly where its crumbly disintegration has produced a ledgelike feature. It is thirty to sixty feet above the lower contact, which is the lower chilled phase of the sill. Where the contact is transgressive and cuts across the bedding planes at King's Point, it is usually paralleled by the olivine layer. The olivine layer is distinctly coarser than the normal diabase. Both the upper and lower surfaces are somewhat undulose. From a short distance both surfaces appear to be sharply defined, but closer scrutiny often reveals gradational contacts with the normal diabase,and microscopic evidence indicates gradational contact in all cases.

North of Alpine the lower part of the sill is not visible except near Nyack, and though an olivine diabase layer may be present it is concealed by talus. The olivine layer is not seen at Hook Mountain north of Nyack, though the lower part of the sill is exposed.(F. Walker, 1940)

Grains throughout most of the thickness of the sill are of medium size, coarse enough to be clearly visible with the unaided eye. Grains averaging 0.5 to 1mm are common in the coarse upper part of the sill. As the minerals are about half light(largely plagioclase) and half dark(largely pyroxene with lesser olivine), the resultant rock has a dark speckled appearance.

The coarsest zone, above the middle of the sill, contains patchy streaks of micropegmatite up to two feet thick. These coarse-grained streaks consist of

quartz and alkili feldspar intergrown in graphic or micrographic textures with coarse blades of pyroxene. Late quartzofeldspathic veins up to three inches in diameter fill fractures in both the upper and lower chilled zones. The distinctive subophitic or ophitic texture of this and other diabases is attributed to simultaneous crystallization of the plagioclase and pyroxene.

Chemistry & Mineralogy: Not only does the grain size vary, but also the mineralogy. Olivine amounts to about one percent in the upper and lower chilled zones and increases up to twenty to twenty-five percentiin the olivine layer. The olivine is Fo_{81-79} in the chilled contact, Fo_{77-55} in the olivine layer, and Fo Fo_{20-27} in the late stages. It tends to be euhedral and in some cases is surrounded by a reaction rim of pyroxene. The earlier pyroxenes in the lower third of the sill consist of coexisting hypersthene and augite. The later pyroxenes, in the upper two-thirds of the sill, consist of pigeonite and augite, these becoming more iron-rich as crystallization proceeds. Plagioclase in the Palisade Sill is intermediate(An_{61-66}) at the chilled contacts, high in calcium near the base(An_{64}), and progressively lower(An_{37}) near the top. Minor minerals include ilmenite and titaniferous magnetite, small flakes of brown biotite or grains of dark-green horneblende as rims on pyroxene and iron oxides, fayalitic olivine, micrographic intergrowths of quartz and alkili feldspar, and fine needles of apatite.

The granophyre forms fine to coarse grained lenticular masses up to one hundred feet thick, paralled to and near the upper contacts of the sill. Miarolitic cavities up to an inch across occur. The granophyres also contain sodic plagioclase, horneblende, biotite, or iron-rich clinopyroxene, and minor titaniferous iron oxide and apatite.

Chemically, this diabase sill represents normal tholeiitic basalt. Samples from the olivine-rich layer, as would be expected, tend to be somewhat higher in MgO and lower in Al_2O_3 and Na_2O. A few samples of the normal diabase are higher

in Al_2O_3(up to 16.54%) than the olivine diabase, and lower in TiO_2(down to 0.74%), and lower in MnO(down to 0.03%), suggesting an affinity with high-alumina basalt of the basalt, andesite, rhyolite association. Chemical trends involve an increase upward in alkalis and iron, and a decrease upward of MgO. The granophyre is enriched in SiO_2, alkalis, and iron, and is depleted in MgO and CaO.(Hyndman, 1972)

Origin: The main guide to the pre-emplacement history of the magma is provided by the microphenocrysts in the basal chilled diabase, but this relates only to the original magma phase. Examination of this contact diabase at six locations shows that it contains olivine, pyroxene, and rare plagioclase microphenocrysts. Olivine microphenocrysts are either euhedral, skeletal, or partially resorbed and have an average composition of Fo_{80}. Most of the pyroxene microphenocrysts are augite with slightly resorbed grain margins, though a few are euhedral or subhedral. They commonly form glomeroporphyritic aggregates that may also include an occasional bronzite grain. Because of the uniform composition and mineralogy of the chilled diabase, and the consistent distribution of microphenocrysts, it was concluded that the magma emplaced was homogenous and rapidly injected.

Microphenocrysts in the chilled diabase presumably represent the solid phases in equilibrium with the liquid immediately prior to the emplacement of the magma. During the emplacement many phenocrysts suffered mechanical deformation and strain. Texture, grain size, and metastable mineral associations indicate that the contact diabase chilled rapidly. Olivine, in particular, and to a limited extent augite, showed some instability in the sill environment, but in the case of pyroxene this is more noticeable in grains a small distance from the contact(25 to 30 feet) where cooling is a little slower, and where the number of pyroxene aggregates increases due to settling. A few of these, including individual bronzite grains, contain an outer zone of freshly crystallized augite;

others are enveloped by aggregates of augite and a few pigeonite grains. It seems that from the habit of the microphenocrysts in the marginal zone of the sill, the sill environment was not greatly different from the environment where the magma was located immediately before its emplacement. Probably temperature was the most significant difference, and variation in olivine composition, in particular, is sensitive to temperature change.

Mobilized magma mush was repeatedly forced up from the point of generation at depth to a fairly shallow reservoir, where it became mixed and lingered sufficiently long to establish a fractionation gradient and equilibrium between the liquid and solid phase. During the pause in the reservoir, the magma lost much heat by conduction through its walls and by the melting of crystals incorporated at depth. This reservoir developed in an environment where olivine of a composition Fo_{80} crystallized in equilibrium with a tholeiitic liquid containing about three percent normative quartz. The reservoir expelled magma of this fractionation stage first. Magma of a more advanced fractionation stage containing about five percent normative quartz was expelled during the second emplacement.

Many of the clues on the petrogenesis of the sill are in the Mg-olivine later and the internal chilled contact. The layer and the internal contact have been described in detail, and it has been shown that the occluded chilled contact in the Haverstraw area has some similar features to the Mg-olivine layer; a common origin for both seems likely. Both were formed at the junction between two magma phases, the first being partly crystallized and differentiated before the second was emplaced. It was during the crystallization that followed that the Mg-olivine layer was formed, and the reversals developed in the fractionation trend of each mineral series, both in the olivine layer and in the internal chilled contact. When equilibrium was established between the phases, differentiation proceeded on a normal course toward iron, silica, and alkali enrichment.

Chemical evidence shows that the intrusion contains two magma phases. The

second was much larger, and of a later fractionation stage than the first, and it appears to have intruded the first above the chilled dolerite stage at King's Bluff, the early dolerite stage at Englewood Cliff, and an early pigeonite stage at Haverstraw. On the grounds of mechanical efficiency it is unlikely that the second magma stage sandwiched laterally into a hot but completely crystallized first phase, wedging it apart along its length; it is more probable that the magma gained access by exploiting the weakest and mainly liquid portion of the first intrusion.

Pseudomorphs after olivine in the diabase immediately below and above the contact at the Haverstraw location suggest that the second magma contained microphenocrysts upon emplscement, and the altered glassy mesostasis suggests that some undercooling occurred. It is apparent that the second phase, like the first, was rapidly emplaced and probably homogenous. If pressure can be assumed to be constant after the injection of the second phase, the mineralogical differences between the dolerites below and above the contact result mainly from the difference in temperature of crystallization between them, because analyses show that the major elemental composition of both dolerited are very similar. About a 25 degree centigrade rise in temperature in the contact zone would have been sufficient to move from a pigeonite stability field to a bronzite stability field with progressive crystallization.

The internal chilled dolerite at the King's Bluff location contains more plagioclase microphenocrysts and orthopyroxene than the basal chilled dolerite of the first phase. This suggests that the second phase was cooler than the first upon emplacement, as Richter and Murata(1966) have shown that the coolest and most silica-rich Kiauean lavas were those with plagioclase and orthopyroxene microphenocrysts in addition to olivine. Cooler emplacement is also consistent with the second magma being of a more advanced fractionation stage than the first. The bronzite microphenocrysts, above the internal contact at Haverstraw,

were introduced with the second phase magma, as their composition is more Fe-rich than those in the early diabase of the first phase above the chilled selvage at Englewood Cliff.

Following the injection of the second phase, a cooling gradient developed across the contact because of the differential in temperature. Another, and probably more severe, gradient developed within the second intrusion, suggesting that it was emplaced by a series of injections that directed the hottest magma towards the top half. Because of the gradient, the initial olivine crystallizing toward the base was in the range Fo_{63-55}, whereas that crystallizing in the top half was in the range Fo_{77-69}. In the late stages of crystallization, the top half yielded olivine in the range Fo_{69-58}.

Olivine crystallization in the second phase magma was accompanied by early plagioclase and probably early augite. These phases grew by progressive zoning and compounded together during their fall to the advancing framework of crystallization at the bottom coolong surface of the sill, where they lodged. The layer would have thickened rapidly by fractional crystallization relative to the normal advance of crystallization in the intrusion, because it is the residual accumulation of all the heavier-than-liquid phases that crystallized during the period of olivine formation. With the cessation of olivine crystallization the layer was abruptly completed, and the main stage of gravitational differentiation in the intrusion gradually stopped. After the rapid build-up of the olivine layer, progressive crystallization continued in the layer until all the interstitual liquid had crystallized.

The olivine layer accumulated during the quiescent magma state that existed while the temperature variation in the multiple intrusion was establishing a cooling gradient consistent with that which normally exists in a simple sheet intrusion during crystallization. Thus, while thermal equilibrium was being established between the magma phases, a pause occurred in the general cooling trend

of the intrusion, during which time the layer and its distinctive babbroic texture developed. After the formation of the layer, progressive crystallization of the intrusion continued, and fractional crystallization proceeded on a normal course toward iron, silica, and alkali-enrichment until crystallization of the sill was complete.(K. L. Walker, 1969)

THIN SECTIONS

The sections, numbered 7 through 14, cover a portion of the basal dolerite from 40 to 47 feet above the lower contact of the Palisades Sill and the Newark Formation. The samples were taken from a location one mile south of the George Washington Bridge on the west side of the Hudson River. Grain texture is generally ophitic to subophitic.

Clinopyroxenes: Grains are anhedral, showing moderate relief and cleavage in two directions. The grains are up to 4mm in length and show polysynthetic twinning along (100). Most grains are augite, as indicated by 2V angles greater than 40 degrees. Some grains have a 2V angle less than 40 degrees and a biaxial figure that appears uniaxial, indicating pigeonite. The total percentage of groundmass that is comprised of clinopyroxene ranges from 40 percent in the lower sections down to 30 percent in the upper sections, a result of increasing alteration. The percentage of clinopyroxene that is pigeonite goes from 30 percent in the lower sections decreasing to 5-10 percent in the upper sections.

Plagioclase: Grains are euhedral, ranging in size from 0.05mm to 3mm. Elongate grains show low interference colors and both albite and simple twinning under crossed nicols. Plagioclase comprises up to 45 percent of the groundmass, lessening with increasing height through the sections. Little or no zoning is evident, indicating that the grains were separated from their parent melt by gravitational fractionation. Further proof of this is found in the decreasing percentage of

anorthite content as one proceeds up the series of thin sections. Percentages were determined from the extinction angles of twinned grains through the use of the Michel-Levy method. Grains in slide 7 (40' above the lower contact) were of the average composition An_{98} . Grains showed lesser percentages of anorthite in the higher sections; An_{55} in section 9, An_{48} in section 10, and An_{44} in section 11. At this point, the trend is interrupted, as the percentage of anorthite again increases: reaching a peak of An_{50} in section 13. The percentage of anorthite again decreases (An_{44} in section 14). This fluctuation was likely caused by the emplacement of the second magma phase, with subsequent increase in the temperature gradient of the sill. This resulted in the precipitation of higher temperature plagioclase(with concurrent increase in the anorthite content). When equilibrium was again established, the fractionation process resumed its normal course, crystallizing plagioclase grains with decreasing anorthite content.

Olivine: Olivine was present either in small percentages or not at all in most thin sections. Where present, the grains are subhedral and range in size up to 1mm. Percentage of olivine increased dramatically in section 12(45' above the lower contact), then dropped off to nothing in sections 13 and 14. In section 12, small euhedral grains of olivine are scattered across both plagioclase and orthopyroxene phenocrysts, giving the rock a poikilitic texture. The grains are 0.02mm to 0.3mm across, showing relatively high relief, and when the nicols are crossed, second order colors. Larger subhedral grains occur, ranging in size up to 1mm. Total percentage of olivine in section 12 is 20 percent.

Horneblende: Horneblende appears as small grains 0.1 to 0.5mm across. Grains are pleochroic green to light green or red to brown. Brown and green varieties occurring in the same grain is not uncommon. Horneblende occurs in all sections in percentages of 2 to 8 percent.

Serpentine: Serpentine occurs in interstitial masses that show wavy extinction under crossed nicols. Under normal light it appears light green. The percentage increases as fractionation increases, a result of increased volatile constituents available to hydrothermally alter earlier formed pyroxenes. Antigorite, a form of serpentine which shows a unique denticular pattern under crossed nicols, occurs in section 13, and to a lesser extent in section 14. Groundmass percentage of serpentine reaches a maximum of 20-25 percent in the uppermost sections.

Accessories

Biotite: Appears in all sections, usually in the form of scattered subhedral flakes that are pleochroic brown to red. Grains show distinctive mottled(birds-eye) extinction under crossed nicols.

Zircon: Occurs as small rounded grains ranging in size up to 0.05mm that show extremely high relief. Where it occurs in biotite, it forms dark halos, a result of emmissions from unstable radioactive isotopes in the zircon crystals.

Apatite: Occurs in most but not all sections in extremely small amounts. Apatite needles appear pale blue, showing high relief, and reach a maximum length of 0.05mm.

Ilmenite/magnetite: Grains appear as black skeletal opaques in all sections, increasing in percentage in the upper sections as fractionation resulted in iron-enrichment of the remaining melt. The crystals were probably once euhedral, but were partially resorbed.

Evidence in the sections indicating gravity fractionation is the decreasing anorthite content in the later(upper) rocks. As the plagioclase crystals formed, they were separated from the melt by gravity, resulting in the differing percentages of anorthite. Had the crystals not been separated from the melt, they would have been subject to diffusion, resulting in all the crystals being of the same percentage anorthite, or at least zoned.

REFERENCES

1. Alling, H. L., 1936, Interpretive Petrology of the Igneous Rocks; McGraw-Hill Book Company, Inc., New York

2. Carmichael, I. S. E., Turner, F. J., & Verhoogen, J., 1974, Igneous Petrology; McGraw-Hill Book Company, New York

3. Ehlers, E. G., 1972, The Interpretation of Geologic Phase Diagrams; W. H. Freeman and Company, San Francisco

4. Ehlers, E. G., & Blatt, H., 1982, Petrology, Igneous, Sedimentary, and Metamorphic; W. H. Freeman and Company, San Francisco

5. Hyndman, D. W., 1972, Petrology of Igneous and Metamorphic Rocks; McGraw-Hill Book Company, Inc., New York

6. Walker, F., 1940, The Differentiation of the Palisade Diabase, New Jersey; Geol. Soc. America Bull., vol. 51, pgs. 1059-1106

7. Walker, K. L., 1969, The Palisades Sill, New Jersey: A Reinvestigation; Geol. Soc. America Special Paper 111